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Transition probabilities for Gd II and a new determination of the solar abundance of gadolinium

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Summary. New lifetime measurements have been performed for 3 levels in Gd II by time-resolved observation of the emitted fluorescence after pulsed laser excitation. New transition probabilities have been deduced for 23 transitions and selected results have been used to derive an improved solar abundance of gadolinium: $A_{\rm Gd} = 1.12 \pm 0.04$.

Key words: laser excitation – transition probabilities – solar abundances

1. Introduction

The knowledge of the solar abundances of the rare earths is important for testing the theories of nucleosynthesis but the uncertainties affecting their determination have often been stressed in the literature (see e.g. Biémont and Grevesse, 1977). The abundance of gadolinium in the sun has been determined by Russel (1929) ($A_{\rm Gd} = 1.6$, in the usual logarithmic scale where $A_{\rm Gd} = \log \frac{N_{\rm Gd}}{N_{\rm H}} + 12.00$), by Wallerstein (1966) ($A_{\rm Gd} = 1.09$, if we adopt $A_{\rm Sc} = 3.1$) and by Righini and Rigutti (1966) ($A_{\rm Gd} = 1.13$). The most recent analysis is due to Grevesse and Blanquet (1969) who found $A_{\rm Gd} = 1.12 \pm 0.15$, and this value has been retained in recent compilations of solar abundances (see e.g. Grevesse, 1984). The last three values have been deduced on the basis of the experimental oscillator strengths of Corliss and Bozman (1962, hereafter abbreviated CB) which have been shown to contain significant excitation-dependent, wavelength-dependent and intensity-dependent errors (see, e.g., Corliss and Tech, 1976; Corliss, 1967; Bell and Upson II, 1971). Though the solar abundances deduced by Wallerstein (1966), by Righini and Rigutti (1966) and by Grevesse and Blanquet (1969) are in agreement and though they agree reasonably well with the meteoritic abundance as adopted in recent compilations ($A_{\rm Gd} = 1.07 \pm 0.02$, according to Anders and Ebihara, 1982), these results need to be checked on the basis of new oscillator strengths in order to verify whether this agreement is fortuitous or not.

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In this work, radiative lifetimes were measured for three levels of the gadolinium ion. The oscillator strengths were determined from the branching ratios of the selectively populated levels.

2. Lifetimes and branching ratio measurements

A pulsed laser was employed for selective excitation of the Gd II ions produced in a diffusing pulsed hollow-cathode discharge. This was combined with time-resolved detection of the emitted fluorescence light selected by a monochromator. The same technique was employed in an earlier paper by Bergström et al, (1986). The ions were produced by cathodic sputtering in a large bore low pressure hollow-cathode. Gadolinium turned out to have a low sputtering yield in the noble gas discharge. A considerable improvement in ion production was obtained by using a cathode consisting of both Ta and Gd. The sample forming the cathode had the form of a Ta cylinder with a Gd bottom plate having a 1 mm hole. The hole in the cathode bottom plate served as a nozzle for forming the ion beam. The beam was extracted into a high vacuum (10^{-4} Torr) scattering chamber by means of diffusion due to the pressure gradient. The discharge conditions for running in a pulsed mode were typically 20 kW with a pulse duration of 10 μs and a repetition rate of 10 Hz. A separate 120 mA d.c. discharge was sustained in the tube to obtain a proper pulsed operation. The laser system consisted of a dye laser pumped by a frequency-doubled Nd:YAG laser. After frequency-doubling and Raman shifting, the laser pulses have a duration of 7 ns. The fluorescence light from the excitation region was focused by two lenses on the entrance slit of the monochromator for wavelength selection, and detected by a fast photomultiplier tube. A boxcar integrator followed by a signal averager were employed to process the signal from the photomultiplier. Finally the laser pulse and the fluorescence curve were transferred to a microcomputer performing the lifetime calculations. In an iterative least-squares program the laser pulse convolved with an expotential, plus background was fitted to the fluorescence curve. For the branching ratio measurements a x–y recorder together with a scanning motor on the monochromator was used. The detection system was calibrated using a Generel Electric DXW 1000 W calibration lamp. Since al the strong lines fall within the detection range of the optical system (wavelengths from Russel, 1950) it was possible to determine transtion probabilities by measuring the branching ratios from the level populated by the laser. The values are given in Table 1 together with the data of CB. The uncertainty for the stronger

Table 1. New radiative lifetimes (τ) and transition probabilities (gA) in Gd II and a comparison with the results of Corliss and Bozman (1962)

Level[a] cm^{-1}	Wavelength λ (Å)	Our data gA (10^8/s)	CB gA (10^8/s)
$^{10}D_{7/2}$ 29242 ($\tau=6.3$ ns)	3418.7	2.8	2.2
	3449.6	1.1	0.64
	3494.4	4.1	2.8
	3872.6	0.1	0.2
	3994.2	0.7	1.1
	4037.9	2.4	1.2
	4098.9	1.4	0.9
$^{8}D_{7/2}$ 30009 ($\tau=3.5$ ns)	3331.4	4.4	2.7
	3360.7	3.4	1.6
	3712.7	6.9	5.6
	3760.9 3763.3	1.7	0.6 0.4
	3839.6	3.1	2.2
	3875.5	0.3	0.4
	3974.0	1.7	1.3
$^{10}D_{11/2}$ 30101 ($\tau=4.3$ ns)	3392.5	3.5	2.2
	3454.1	2.5	1.1
	3549.4	9.6	8.4
	3957.8 3959.4	3.8	2.6 1.6
	4037.3	3.9	3.1
	4130.4	3.2	4.9
	5252.1	0.1	–

[a] Designations from Russel (1950)

lines, e.g. the ones used in the solar analysis, are 10%. The total strength of infrared lines, lines not seen because of the detection limit in our system and the weak lines detected but not given in the table were esimated to 1, 6 and 5% of the total decay for the levels 29242, 30009 and 30101 cm^{-1}, respectively. Our transition probabilities are on the average somewhat higher than the CB values but no large discrepancies appear.

3. Solar results

Gadolinium is well represented in the photospheric spectrum through Gd II lines (Moore et al., 1966, hereafter abbreviated MMH). Among the transitions depopulating the 3 levels for which lifetimes have been measured in this investigation, 11 lines have been identified by MMH as being due or possibly due to Gd II. The equivalent widths of these lines have been measured on the high resolution Jungfraujoch spectra (Delbouille et al., 1973). It is important, however, in the final analysis to exclude all the lines which are significantly affected by blending since these lead to systematically too high abundance values. Among the initial sample of 11 lines, we have successivley eliminated the following lines:

– $\lambda\lambda$ 3392.498, 3449.631, and 3959.542, which are identified as possibly due to Gd II (Gd II?) in MMH tables but which are very difficult to measure;

Table 2. Solar data and results for Gd II

λ_{sun}[a] (Å)	E_{low}[b] (eV)	W_λ^{sun}[c] (mÅ)	$\log gf$[d]	A_{Gd}[e]	Weight[f]
3331.397	0.00	10.5	−0.14	1.11	2
3439.229	0.38	10.5	0.15*	1.17	2
3494.412	0.08	10.6	−0.12	1.17	1
3697.747	0.03	8.6	−0.28*	1.12	1
3712.717	0.38	10.2	0.15	1.11	1
3796.391	0.03	13.2	0.07*	0.97	1
4037.913	0.56	3.8	−0.23	1.07	1
4085.574	0.73	6.3	0.07*	1.17	2

[a] From Moore et al. (1966)
[b] Lower excitation potential in eV
[c] Equivalent width measured on Jungfraujoch spectra (Delbuille et al., 1973)
[d] $\log gf$ as deduced in this work; the starred values have been obtained from Corliss and Bozman's tables according to the relation: $\log gf = \log gf_{CB} + 0.11$
[e] Abundance in the logarithmic scale: $A_{Gd} = \log(N_{Gd}/N_H) + 12.00$, calculated with Holweger and Müller (1974) model and a microturbulence of 0.85 km/s
[f] Weighting factor (see the text)

– $\lambda\lambda$ 3549.371 and 4098.901 which lead to "high" abundances ($A = 1.52$ and 1.39 respectively). These lines could be blended with Tb II and Nd II contributions (at λ 3549.36 and λ 4098.91; Meggers et al., 1975);

– λ 4130.368: this line is blended with a V I transition at λ 4130.375 [$\log gf = -0.76$ according to Kurucz and Peytremann (1975, hereafter abbreviated KP)]. The estimated contribution to the equivalent width is 0.7 mÅ but the reliability of the gf value is difficult to assess;

– λ 3418.732: the corresponding abundance is very high ($A = 1.85$): this line is probably perturbed by an unknown contributor. The possible contribution due to Ti II (λ 3418.730) and Cr I (λ 3418.736) are negligible ($W_\lambda^{calc} < 0.1$ mÅ) according to the f-values calculated by KP.

To the remaining lines at $\lambda\lambda$ 3331.397, 3494.412, 3712.717, and 4037.913, we have added 4 additional lines identified as Gd II by MMH at $\lambda\lambda$ 3439.229, 3697.747, 3796.391, and 4085.574. These 8 lines whose equivalent widths have been carefully remeasured were found to be unblended according to the available line lists (KP; Meggers et al., 1975). The line at λ 3697.747 could be perturbed by the Ru I line at λ 3697.76 ($\log gf = -0.93$, according to CB). The corresponding contribution ($W_\lambda^{calc} = 0.1$ mÅ) is small but has nevertheless been taken into account. For the levels at 29242, 30009, and 30101 cm^{-1} whose lifetimes have been measured in this work, the ratio $\tau_{CB}/\tau_{this\ work}$ (where τ_{CB} is the lifetimes deduced from CB tables) is respectively 1.34, 1.41, and 1.11 leading to a mean value of 1.29. Consequently, for the 4 lines mentioned above, a mean correction to CB gf-values was applied according to the relation: $\log gf = \log(gf)_{CB} + 0.11$, and these corrected oscillator strengths were used for the solar analysis.

The eight Gd II lines retained for the final analysis are listed in Table 2. The solar abundance of gadolinium has been derived for each line using direct integration of the line profiles assuming local thermodynamic equilibrium. We have adopted the photospheric model of Holweger and Müller (1974). Arguments in favour of this model have been presented previously (Biémont et al., 1981). Each A_{Gd} value has been assigned a weighting factor (1 or 2: see Table 2) according to the difficulty of locating the continuum and of measuring the lines (see, e.g., Biémont et al., 1981, 1982). The adopted microturbulence ($\xi = 0.85\,\mathrm{km\,s^{-1}}$, isotropic and independent of the optical depth) is consistent with the results obtained by Blackwell and Shallis (1979) and by Blackwell et al. (1980).

The lines considered in this analysis are weak and consequently the individual abundances are independent of the approximations used for calculating the damping. Hyperfine structure has not been considered in the computations reported here but these effects are expected to be negligible (see Clieves and Steudel, 1979) for the weak lines considered in this paper. Line blanketing effects below 4500 Å was considered carefully and an extra-opacity source below that wavelength limit was introduced in the computations (see e.g., Magain, 1983). The ionization potentials of Gd I and Gd II were adopted from Martin et al. (1974) and the partition functions were calculated according to the Chebyshev expansions proposed by Van Diest (1980).

The mean abundance value deduced from the 8 lines of Table 2 is 1.12 ± 0.04, where the uncertainty represents twice the standard deviation of the mean. This value confirms the results deduced by Wallerstein (1966), by Righini and Rigutti (1966) and by Grevesse and Blanquet (1969) but the uncertainty affecting the solar abundance of gadolinium is considerably decreased because atomic and solar data used in this analysis have been considerably improved. The solar value is in agreement with the meteoritic abundance deduced by Anders and Ebihara (1982) ($A = 1.07$, if we adopt the same normalization as Grevesse, 1984).

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